Higgs-Exempt No-Scale Supersymmetry and its Experimental Signatures

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Outline

- The Supersymmetric Flavor Problem
- A Solution: Small Scalar Soft Terms
- RG Running and the Mass Spectrum
- Implications $\longrightarrow$ Light Sleptons:

1. Acceptable Bino dark matter
2. Multi-lepton events at colliders.

Motivation: the SUSY Flavour Problem

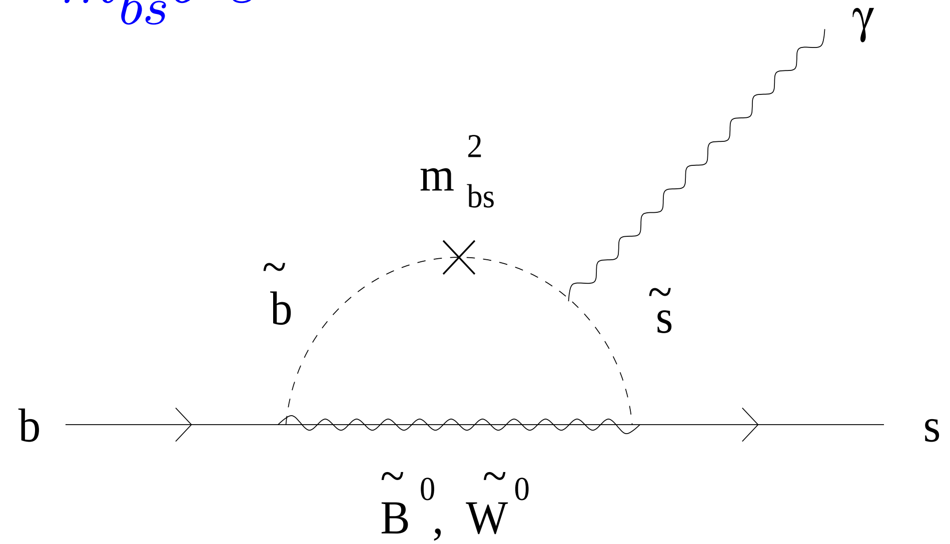
- Low-scale supersymmetry (SUSY) is a well-motivated extension of the Standard Model.

- Supersymmetry can only be an approximate symmetry.

  $\mathscr{L} \supset \mathscr{L}_{soft} \supset -m^2|\phi|^2 - A\,\phi^3 - M\,\lambda\lambda$

- The m^2 and A terms can induce too much flavour mixing.

  e.g. $\quad \mathscr{L}_{soft} \supset -m^2_{bs}\tilde{b}^*\tilde{s} \quad \longrightarrow$



Approaches to the SUSY Flavor Problem

1. Introduce a new flavor symmetry that is broken above M_W.

   Such models are often very complicated.

2. Take $\sqrt{|m^2|},\ A \gg 1000$ GeV, but $M_{gaugino} \lesssim 1000\,\text{GeV}$

   $\rightarrow$ Split Supersymmetry

   In doing so, we lose the explanation for $M_W \ll M_{\text{Pl}}$.

3. Arrange for $\sqrt{|m^2|},\ A \rightarrow 0$, but $M_{gaugino} \neq 0$,

   at a scale much larger than M_W.

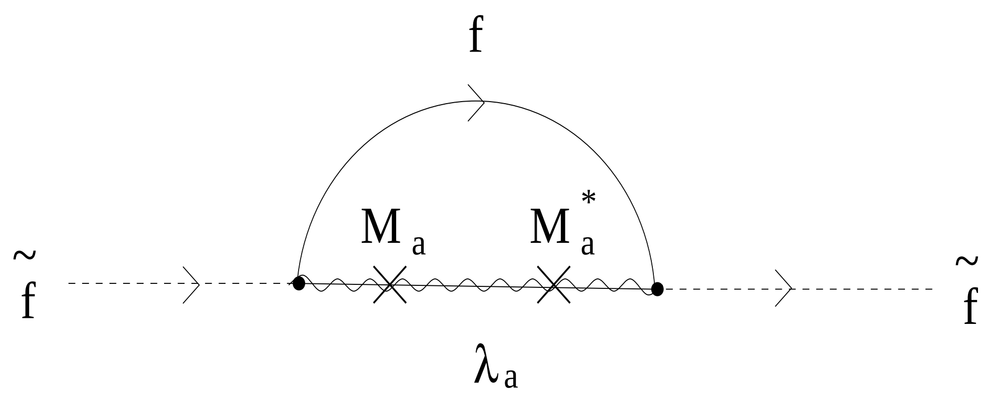
   $\rightarrow$ Small Scalar Soft Terms (Splat Supersymmmetry)

   This is the approach we will consider.

Small Scalar Soft Terms

- Suppose all m^2 and A soft terms vanish at some scale $M_{input} \gg M_W$, but the gaugino masses M_a do not.

- Non-zero values for the m^2 and A terms are generated as the theory is RG-evolved down to M_W.



- The soft scalar soft terms generated are nearly flavour universal, and do not generate too much flavour mixing.

Obtaining Small Scalar Soft Terms

- These can arise in several ways:

1. No-Scale models [Cremmer *et al.* '83, Ellis *et al.*'84]

   - A form of gravity mediation motivated by certain string theory compactifications.

2. Gaugino mediated SUSY breaking [Chacko *et al.*'99, Kaplan *et al.*'99]

   - XD scenario with gauge multiplets in the bulk but chiral multiplets confined to branes.

3. Strong conformal dynamics [Nelson+Strassler '00, Luty+Sundrum '01]

   - Interactions cause the scalar soft terms to flow to zero.

Exempting the Higgs

- If all m^2 and A terms vanish at M_{input}, the lightest superpartner is a charged slepton.
  ($M_{input} \leq M_{GUT} \simeq 2 \times 10^{16}$ GeV, universal gaugino masses)
  [Schmaltz+Skiba '00, Komine+Yamaguchi '00, Baer *et al.* '02, Balazs+Dermisek '03]

- This can be a problem for cosmology.

- To avoid this, we consider an extension of the small scalar soft terms scenario that doesn't introduce flavour problems:

$$|m^2_{H_u}| \sim |m^2_{H_d}| \sim M_a^2 \gg m^2_{\tilde{f}},\ A_f \quad \text{at} \quad M_{input}.$$

$\longrightarrow$ Higgs boson soft masses don't get squashed at M_{input} like the rest.

Model Setup

- We consider the following soft terms at scale $M_{input} = M_{GUT} \simeq 2 \times 10^{16}$GeV:

  – $m^2_{\tilde{f}} = 0, \quad A_f = 0$

  – $M_1 = M_2 = M_3 = M_{1/2} \quad \leftrightarrow \quad 1, 2, 3 = U(1), SU(2), SU(3)$

  – $m^2_{H_u}, \quad m^2_{H_d}$ unfixed.

- The independent free parameters of the model are:

$$M_{1/2}, \quad m^2_{H_u}, \quad m^2_{H_d}, \quad \tan\beta, \quad sgn(\mu).$$

Renormalization Group Evolution of Soft Terms

- For universal gaugino masses at M_{GUT}

  the electroweak scale gaugino masses are:

$$\begin{aligned} M_1 &\simeq (0.41)\, M_{1/2}, \\ M_2 &\simeq (0.82)\, M_{1/2}, \\ M_3 &\simeq (2.9)\, M_{1/2}. \end{aligned}$$

- The electroweak scale slepton soft masses are:

$$\begin{aligned} m_E^2 &\simeq [(0.39)\, M_{1/2}]^2 - (0.055)\, S_{GUT} \\ m_L^2 &\simeq [(0.64)\, M_{1/2}]^2 + \frac{1}{2}(0.055)\, S_{GUT} \end{aligned}$$

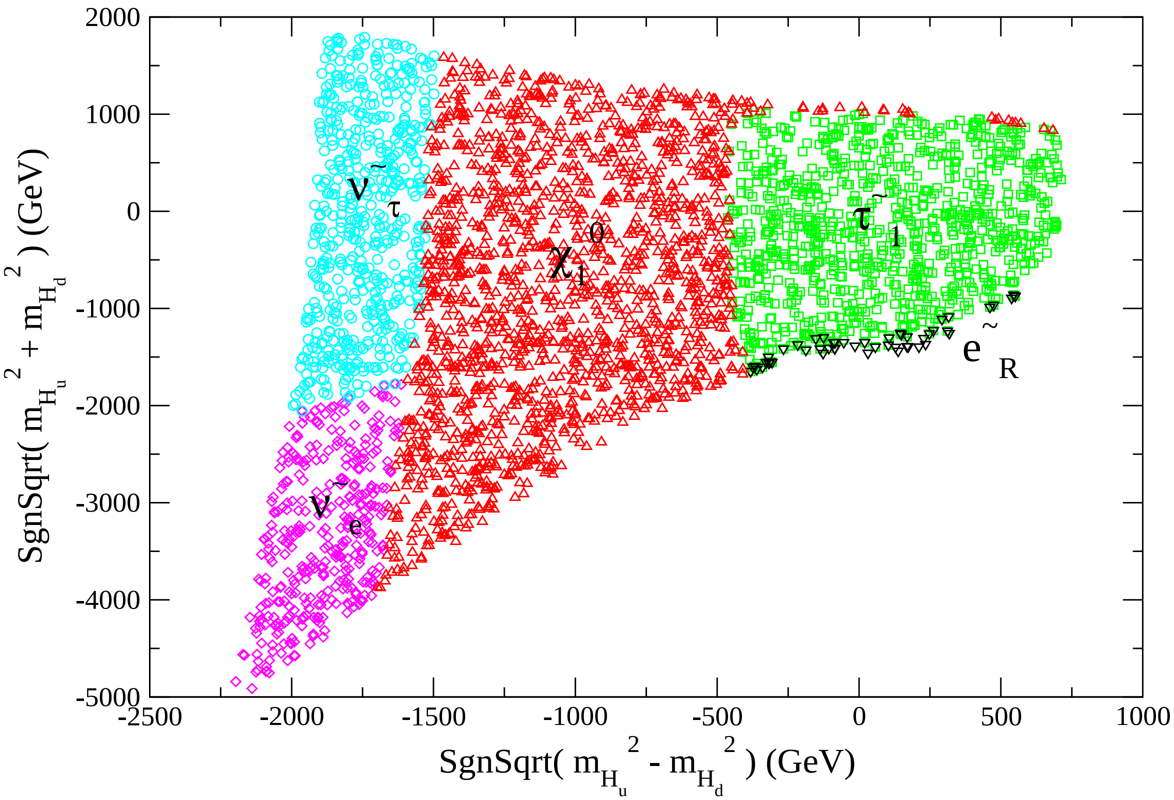
  where $S_{GUT} = (m_{H_u}^2 - m_{H_d}^2)_{GUT}$.

- The low-scale squark masses are considerably larger.

Lightest Superpartners

- $\tan\beta = 10$, $M_{1/2} = 500$ GeV, $sgn(\mu) > 0$.

- Only for $S_{GUT} = (m^2_{H_u} - m^2_{H_d}) < 0$ is the LSP a neutralino.



Features of the Mass Spectrum

- All masses scale with the input gaugino mass $M_{1/2}$.
- Lighter electroweak gauginos

  $\rightarrow$ Higgs mass constraint requires $M_{1/2} > 300\,\text{GeV}$
- Lighter sleptons

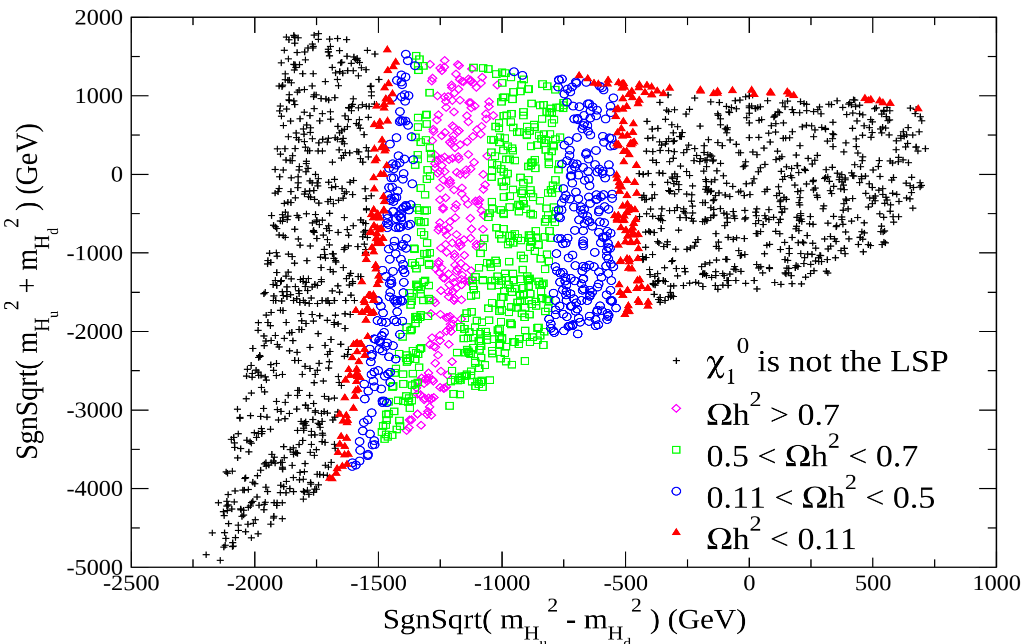
  $\rightarrow$ some sleptons are close in mass to the lightest gaugino
- Heavier squarks and gluino

  $\rightarrow$ these help to push the Higgs mass up

- The light sleptons play a key role in the cosmology and collider signatures of the model.

Light Sleptons #1: Neutralino Dark Matter

- With a universal gaugino mass $M_{1/2}$, the LSP is mostly $U(1)_Y$ gaugino and tends to yield too much dark matter.
- If there is slepton close in mass to the (Bino-like) LSP, they can coannihilate.
- $\tan\beta = 10$, $M_{1/2} = 500$ GeV, $sgn(\mu) > 0$

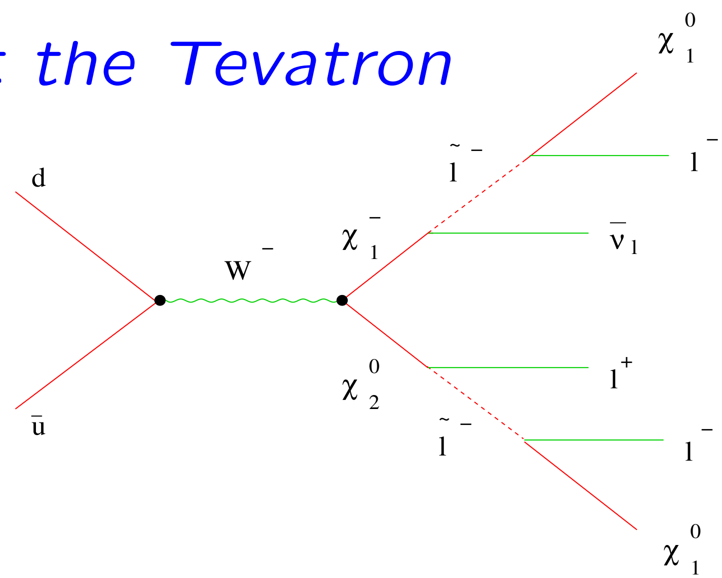


Light Sleptons #2: Leptons at Colliders

- Light sleptons lead to leptonic events at colliders:

$$\chi^0_{2,3,4} \to \tilde{\ell}^{\pm}\,\ell^{\mp} \qquad \text{are kinematically allowed}$$
$$\chi^{+}_{1,2} \to \tilde{\ell}^{+}\,\nu,\ \tilde{\nu}\,\ell^{+}$$

- *e.g. Trileptons at the Tevatron*



Using the set of cuts in [Baer *et al* '99] we find:

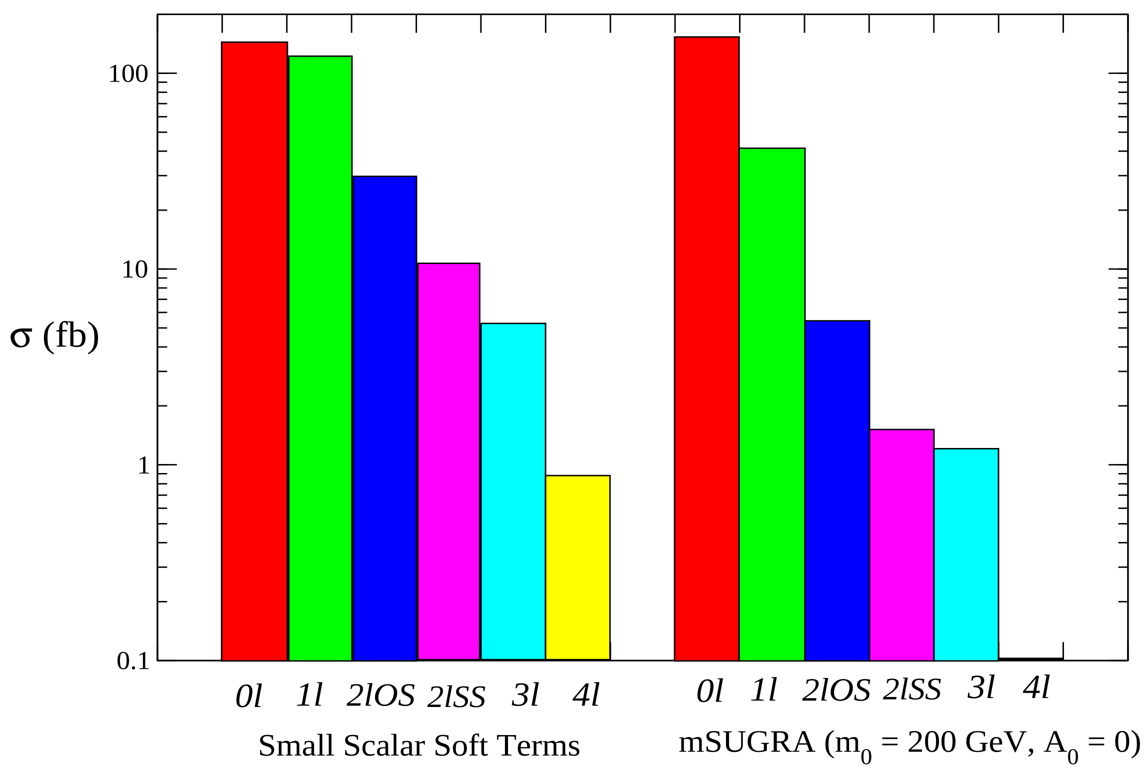
$$\sigma_{3\ell} \lesssim 0.5\,\text{fb} \qquad (\,M_{1/2} = 300\,\text{GeV},\ \tan\beta = 10,\ \text{“HC2” cuts})$$

$$\sigma_{bg} \simeq 0.5\ \text{fb}$$

- With small scalar soft terms, the LHC should be able to discover SUSY with $10\ fb^{-1}$ of data for $M_{1/2} \lesssim 700\,\mathrm{GeV}$.

- Compared to other SUSY scenarios, the ratio of $1\,\ell$ and multi-ℓ events to $0\,\ell$ events is very large.

- For $\tan\beta = 10$, $M_{1/2} = 500\,\mathrm{GeV}$, and simple cuts,



List of Cuts

- Events were simulated using ISAJET 7.74 [Baer *et al.* '06]
- "Lepton" $\Rightarrow$ isolated e or μ with $p_T > 10$ GeV, $|\eta| < 2.5$.
- All Events: $\not{E}_T > 200$ GeV, $\quad S_T > 0.2, \quad n_{jets} \geq 2$.
- $0\,\ell$: $30^o < \Delta\phi(\not{E}_T, j) < 90^o$ with the nearest jet.
- $1\,\ell$: $p_T(\ell) > 20$ GeV, $\qquad M_T(\ell,\not{E}_T) > 100$ GeV
- $\geq 2\,\ell$: $p_T(\ell_{1,2}) > 20$ GeV.

Summary

- Small scalar soft terms at the input scale M_{input} is a simple solution to the SUSY flavour problem.

- Allowing unsuppressed Higgs soft terms allows for a neutralino LSP and doesn't reintroduce a flavour problem.

- This scenario always yields very light sleptons.

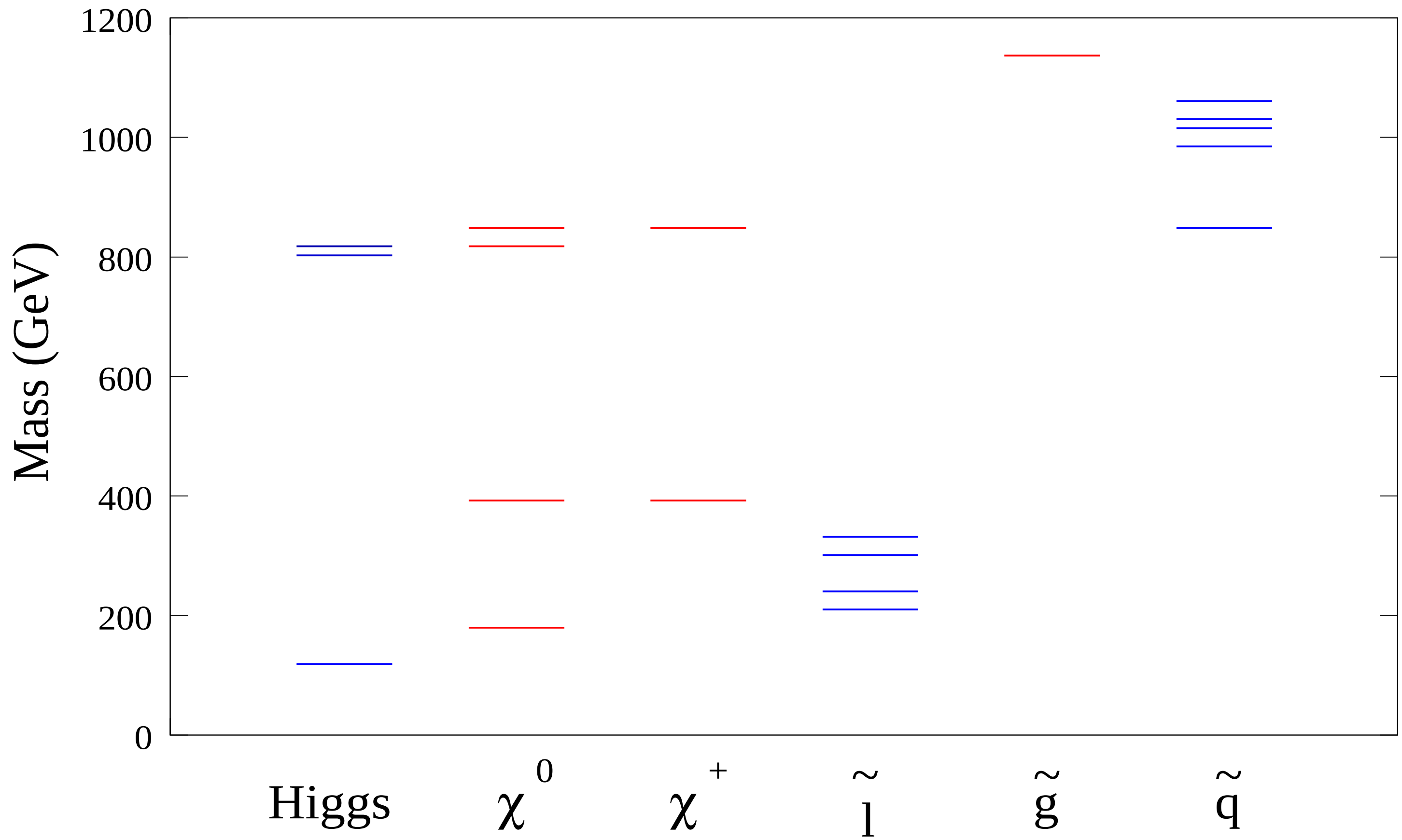
  $\Rightarrow$ acceptable dark matter density through coannihilation

  $\Rightarrow$ many multi-lepton events at the LHC

Extra Slides

Sample Mass Spectrum

- $\tan\beta = 10$, $M_{1/2} = 500$ GeV, $sgn(\mu) > 0$.



RG Evolution of Gaugino Masses

- The RG evolution equation for the gaugino masses is

$$\frac{dM_a}{dt} \simeq -\frac{2\,b_a}{(4\pi)^2}\,g_a^2\,M_a, \quad a = 1, 2, 3.$$

- $\Rightarrow M_a/g_a^2$ is approximately scale-independent.

- If $g_3 = g_2 = g_1 = g_{GUT} \simeq 0.72$ at M_{GUT},
  the electroweak scale gaugino masses are

$$\begin{aligned} M_1 &\simeq (0.41)\,M_{1/2}, \\ M_2 &\simeq (0.82)\,M_{1/2}, \\ M_3 &\simeq (2.9)\,M_{1/2}. \end{aligned}$$

RG Evolution of Scalar Masses

- The RG evolution equation for the soft scalar masses is

$$(4\pi)^2 \frac{dm_i^2}{dt} \simeq -8 \sum_a C_i^a \, g_a^2 \, |M_a|^2 + \frac{6}{5} g_1^2 \, Y_i \, S,$$

where

$$C_i^a = \begin{cases} 0, \ \frac{4}{3}, & a = 3 \\ 0, \ \frac{3}{4}, & a = 2 \\ \frac{3}{5} Y_i^2, & a = 1 \end{cases}$$

and

$$S = (m_{H_u}^2 - m_{H_d}^2) + tr_F(m_Q^2 - 2m_U^2 + m_E^2 + m + m_D^2 - m_L^2).$$

- Because M_3 and g_3 grow large, the scalar quark masses also become large at the electroweak scale.

- The soft slepton masses are smaller,

$$
\begin{aligned}
m_E^2 &\simeq [(0.39)\, M_{1/2}]^2 - (0.055)\, S_{GUT} \\
m_L^2 &\simeq [(0.64)\, M_{1/2}]^2 + \frac{1}{2}(0.055)\, S_{GUT}
\end{aligned}
$$

where $S_{GUT} = (m_{H_u}^2 - m_{H_d}^2)_{GUT}$.

- The mass of the lightest neutralino is usually set by M_1.

- The mass of the lightest slepton is usually less than $min(\sqrt{m_L^2}, \sqrt{m_E^2})$.

- If $S_{GUT} \geq 0$ the lightest superpartner (LSP) is a mostly right-handed scalar lepton.

$$\begin{aligned} M_1 &\simeq (0.41)\, M_{1/2} \\ \sqrt{m_E^2} &\simeq \sqrt{[(0.39) M_{1/2}]^2 - (0.055)\, S_{GUT}} \end{aligned}$$

- This is problematic for cosmology.

- This is the difficulty for most no-scale type models.

- By allowing $S_{GUT} = (m_{H_u}^2 - m_{H_d}^2) < 0$, we can obtain a neutralino LSP.

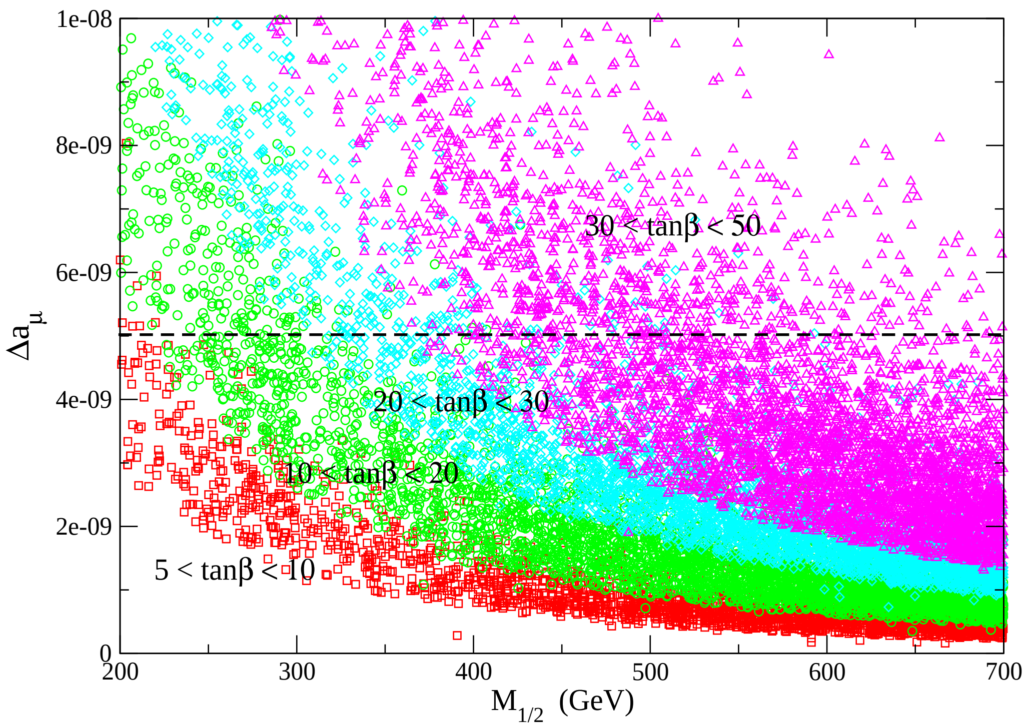
- Higgs soft masses don't introduce a flavor problem.

Light Sleptons #3: Muon Magnetic Moment

- The current value is [BNL-E821, PDG'06]

$$\Delta\left(\frac{g-2}{2}\right) = \Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (2.2 \pm 1.0) \times 10^{-9}$$

- Light sleptons produce additional constributions to Δa_μ.



Direct Detection of Dark Matter

- The Earth encounters a flux of DM particles as it moves along with the galactic rotation.

- DM direct searches look for the interaction of dark matter particles with heavy nuclei.

- The limits from these searches are expressed in terms of an effective LSP-nucleon scattering cross section.

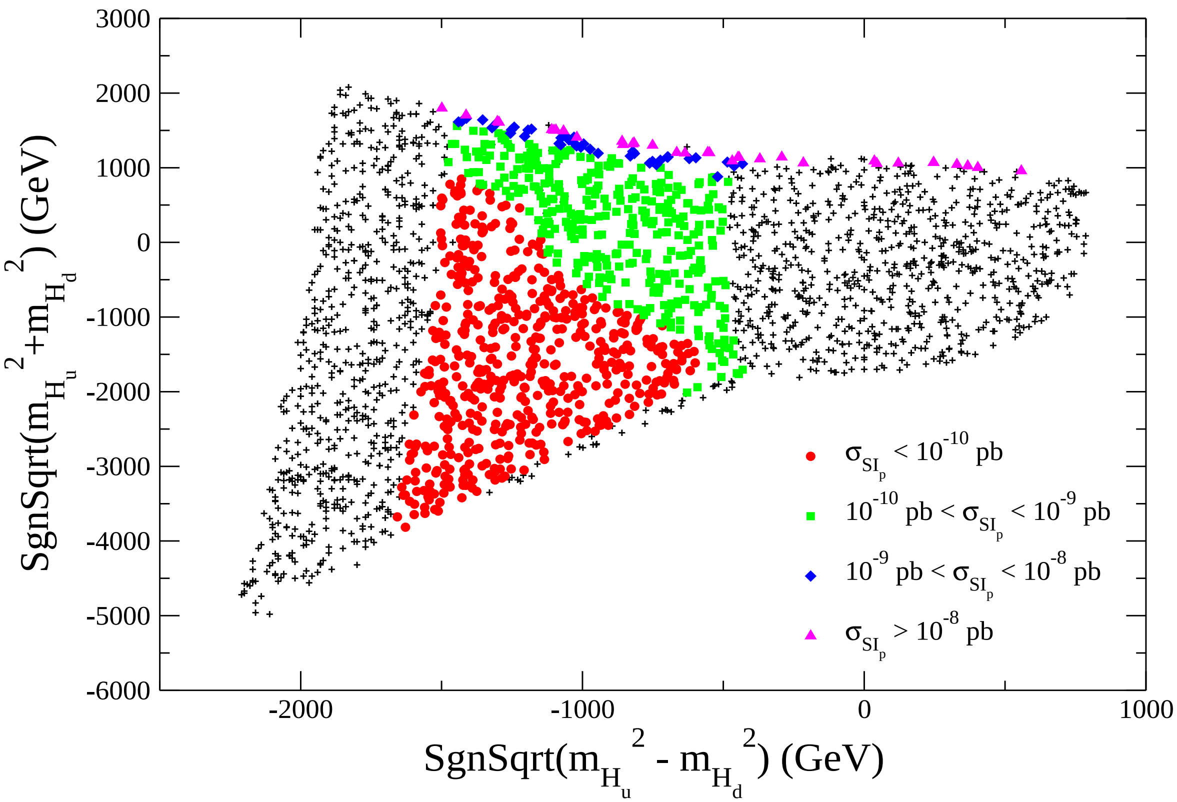
- Currently, the best limit is [CDMS II]

$$\sigma_p^{SI} < 10^{-6}\text{–}10^{-7}\ \mathrm{pb},$$

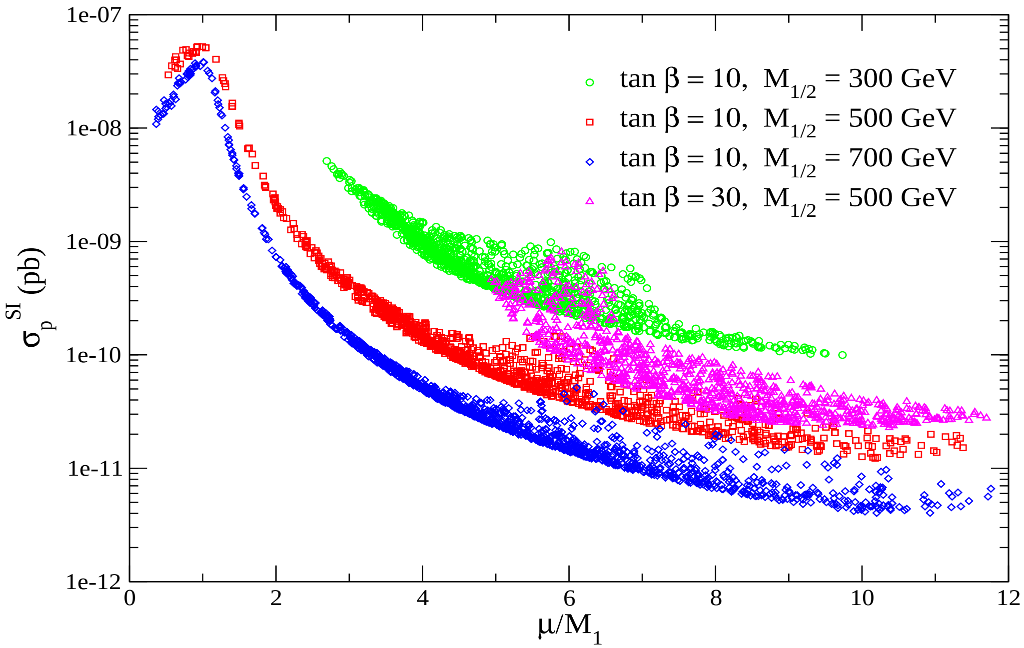
for a DM particle of mass 50-1000 GeV.

- $\tan\beta = 10$, $M_{1/2} = 500$ GeV, $sgn(\mu) > 0$

(σ_p^{SI} was computed using DarkSUSY)



- The direct detection rates lie below the CDMS II bound.
- They increase as μ/M_1 grows smaller and the neutralino LSP develops a larger higgsino component.



- Upcoming direct detection experiments will probe down to about $\sigma_p^{SI} \sim 10^{-9}$ pb.

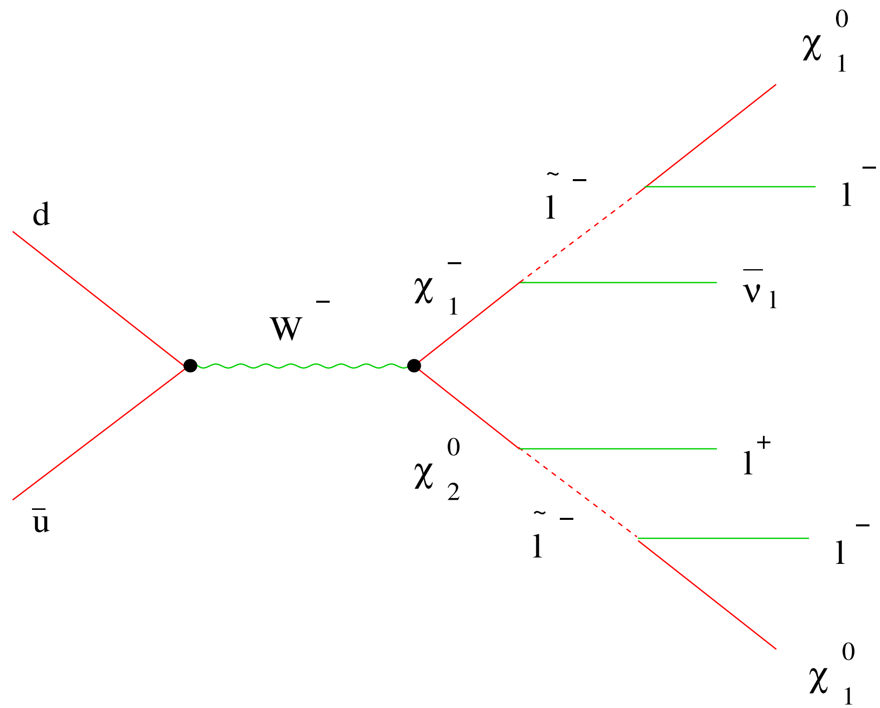
Indirect Detection of Dark Matter

- Dark matter can also induce astrophysical signals.
- Neutralino LSPs can accumulate in the core of the Sun, where they can annihilate into neutrinos.
- Experiments such as Super-Kamiokande and AMANDA have placed bounds on this source of neutrino flux.
- As for the direct detection bounds, the SSST signal is below the current bounds except when μ/M_1 is small.

Signatures at the Tevatron

- The most promising channel at the Tevatron is the trilepton signal.

  e.g.



- Since many of the sleptons are light, the branching ratio for $\chi_2^0 \to \ell^- \tilde{\ell}^+$ is often large.

- Signal events were simulated using ISAJET 7.44 with the following set of cuts [Baer *et al.* '99]

  - 3 isolated leptons

    $|\eta(\ell_{1,2,3})| < 2.5$, $p_T(\ell_{1,2,3}) > 20,\ 15,\ 10$ GeV

  - $\not{p}_T > 25$ GeV.

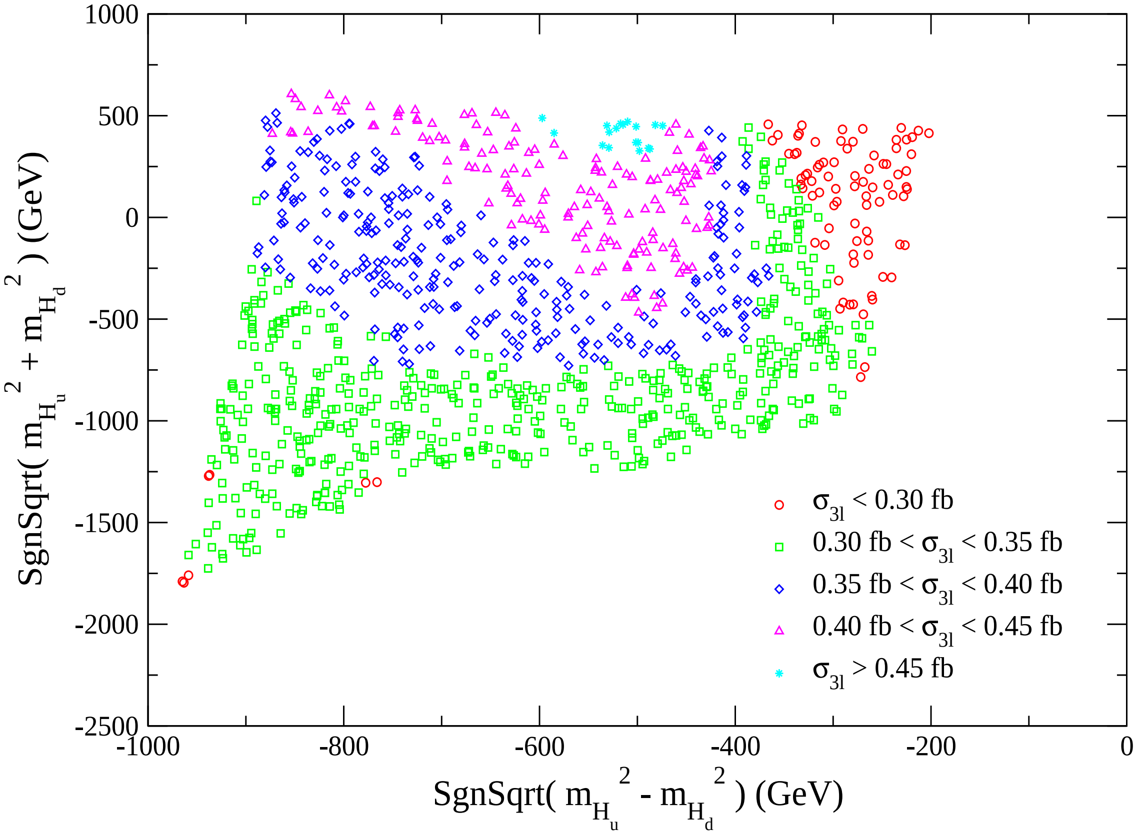
  - lepton momenta not from $W^\pm$ and Z^0 decays

    $12\,\text{GeV} < M_{inv}(\ell^+\ell^-) < 81\,\text{GeV}$ for OS SF lepton pairs

    NOT $60\,\text{GeV} < m_T(\ell, \not{p}_T) < 85\,\text{GeV}$

- With these cuts, the main SM background comes from W^*Z^* and $W^*\gamma^*$ production, and is about 0.5 fb.

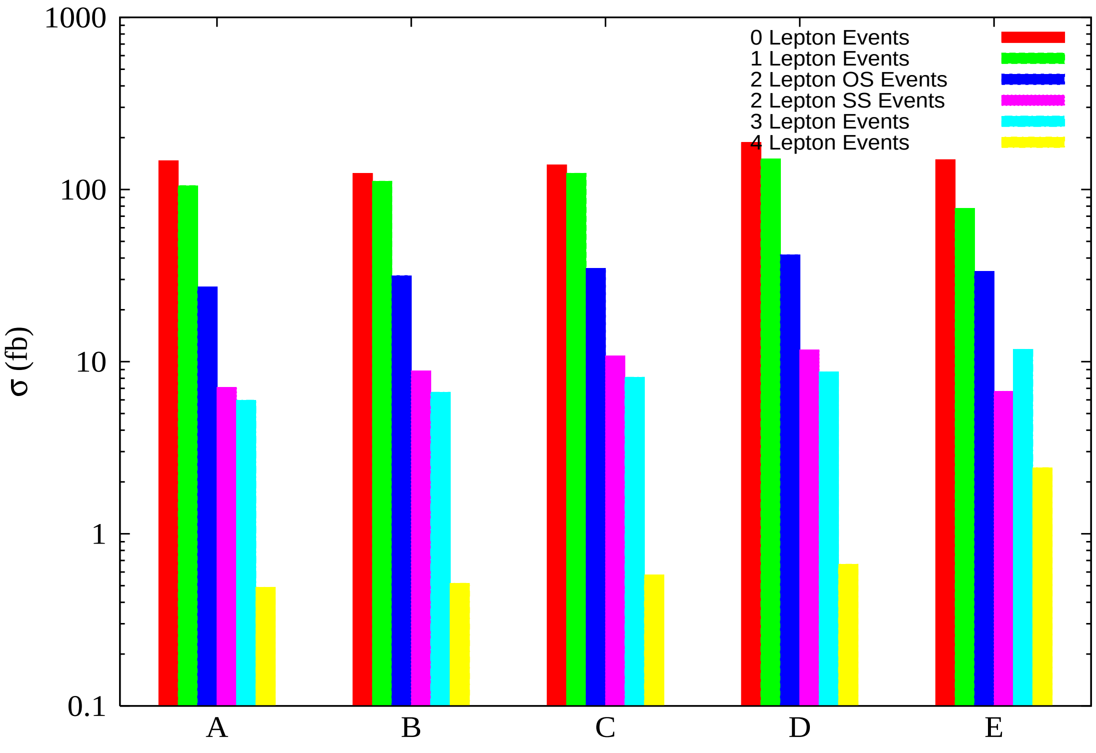
- For $M_{1/2} = 300$ GeV, $\tan\beta = 10$, the signal is about 0.3–0.5 fb.



$\Rightarrow$ possible hints from the Tevatron with 10 fb^{-1} of data?

Signatures at the LHC

- Small scalar soft terms $\rightarrow$ light sleptons $\rightarrow$ leptonic events.
- The distinguishing feature of these scenarios is a high rate for multi-lepton events.
- For $\tan\beta = 10$, $M_{1/2} = 500\,\text{GeV}$, and simple cuts,



- With small scalar soft terms, the LHC should be able to discover SUSY with 10 fb^{-1} of data for $M_{1/2} \lesssim 700\,\mathrm{GeV}$.

- Compared to other SUSY scenarios,
  the ratio of $1\,\ell$ and multi-ℓ events to $0\,\ell$ events is very large.

- The $3\,\ell$ and $4\,\ell$ channels are particularly distinctive.

  Signals:

$$\sigma_{3\ell} = 5 - 10\,fb \qquad\qquad \sigma_{4\ell} \gtrsim 0.5\,fb$$

  SM Backgrounds:

$$\sigma_{3\ell}^{bg} = 0.1\,fb \qquad\qquad \sigma_{4\ell}^{bg} \simeq 0.002\,fb$$